

# $\alpha$ -decay properties of $^{296}118$ from double-folding potentials

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$\alpha$ -decay properties of the yet unknown nucleus  $^{296}118$  are predicted using the systematic behavior of parameters of  $\alpha$ -nucleus double-folding potentials. The results are  $Q_\alpha = 11.655 \pm 0.095$  MeV and  $T_{1/2} = 0.825$  ms with an uncertainty of about a factor of 4.

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Very recently, Sobiczewski [1] has analyzed the decay properties of the yet unknown nucleus  $^{296}118$  using a combination of  $Q_\alpha$  values from mass models and a phenomenological formula for the  $\alpha$ -decay half-lives. This study was motivated by ongoing experiments which attempt to synthesize this heaviest nucleus to date. The present work uses a completely different approach which is based on the smooth and systematic behavior of  $\alpha$ -decay parameters using double-folding potentials [2].

Sobiczewski finds  $Q_\alpha$  values between 10.93 MeV and 13.33 MeV from 9 different mass models. Using the phenomenological formula for  $\alpha$ -decay half-lives of [3], the resulting half-lives for  $^{296}118$  vary by more than 5 orders of magnitude between  $1.4 \mu\text{s}$  and  $0.21$  s. To reduce this uncertainty, three mass models are identified in [1] which describe the masses of nearby nuclei with the smallest deviations: Wang and Liu (WS3+, [4]), Wang *et al.* (WS4+, [5, 6]), and Muntian *et al.* (HN, [7, 8]). In detail, two  $\alpha$ -decay chains are studied for this purpose: the known chain  $^{294}118 \rightarrow ^{290}\text{Lv} \rightarrow ^{286}\text{Fl} \rightarrow ^{282}\text{Cn}$  (hereafter: “chain-1”), and the chain  $^{296}118 \rightarrow ^{292}\text{Lv} \rightarrow ^{288}\text{Fl} \rightarrow ^{284}\text{Cn}$  (“chain-2”) where only the two latter  $\alpha$ -decays are known from experiment. The selection of the mass formulae leads to a restricted range of  $Q_\alpha$  for  $^{296}118$  from 11.62 MeV (WS3+), 11.73 MeV (WS4+), and 12.06 MeV (HN), and the corresponding  $\alpha$ -decay half-lives are 4.8 ms (WS3+), 2.7 ms (WS4+), and 0.50 ms (HN). This range of predictions of almost one order of magnitude for the  $\alpha$ -decay half-life of  $^{296}118$  does not yet include an additional uncertainty of the phenomenological formula of [3] which is on average a factor of 1.34 for even-even nuclei and does not exceed a factor of 1.78 in most cases [3].

In a further study Budaca *et al.* [9] have applied empirical fitting formulae for the prediction of the decay properties of  $^{296}118$ . They obtain a slightly lower  $Q_\alpha = 11.45$  MeV and half-lives of about 3 ms. A very low value of  $Q_\alpha = 10.185$  MeV is derived from mass formulae in [10, 11], leading to predicted half-lives up to minutes for  $^{296}118$ . Half-lives of the order of 1 ms have been obtained in [12] using the WS4+  $Q_\alpha$  and various empirical formulae for the half-life, and similar half-lives slightly below 1 ms were found very recently in [13, 14]

which are also based on  $Q_\alpha$  from WS4+.

For completeness it has to be mentioned that  $\alpha$ -decay is the dominant decay mode of  $^{296}118$ . Partial half-lives of  $^{296}118$  for spontaneous fission have been estimated in [1, 15]; they exceed the  $\alpha$ -decay half-life by several orders of magnitude.

Contrary to the study of Sobiczewski and the other recent calculations for  $^{296}118$  [9–12], the present approach does not use mass models for the prediction of the unknown  $Q_\alpha$  of  $^{296}118$  which is the most important quantity for the prediction of its half-life. Instead, the smooth behavior of parameters is used which is obtained in calculations with systematic double-folding potentials [2]. This method is particularly well suited for the present case where the available experimental results for chain-1 and chain-2 have to be extrapolated only to a very close neighbor. For completeness it should be noted that there is another method for an independent determination of  $Q_\alpha$  from the systematics of  $Q_\alpha$  differences of neighboring nuclei; unfortunately, the published values end at  $^{295}118$  and do not include  $^{296}118$  [16].

The application of double-folding potentials for  $\alpha$ -decay in a simple  $\alpha$ +nucleus two-body model has been described in detail already in [2], and it has been applied and further developed in a series of  $\alpha$ -decay studies in the last years (e.g., [17–27]). Here I briefly repeat the essential points. First, the interaction between the daughter nucleus and the  $\alpha$ -particle is calculated by a double-folding procedure using an effective nucleon-nucleon interaction; for details, see [28]. As in [2], the unknown density of the daughter nucleus is calculated from a 2-parameter Fermi distribution with the radius parameter  $R = R_0 A_D^{1/3}$  which scales with the mass number  $A_D$  of the daughter, and  $R_0$  and the diffuseness  $a$  are taken from the average values of  $^{232}\text{Th}$  and  $^{238}\text{U}$  [29]. The density of the  $\alpha$ -particle is also derived from the charge density in [29]. This results in the double-folding potential  $V_{\text{DF}}(r)$ . The total potential is given by

$$V(r) = \lambda V_{\text{DF}}(r) + V_C(r) \quad (1)$$

with the strength parameter  $\lambda \approx 1.1 - 1.3$  for heavy nuclei [28, 30]. The Coulomb potential is calculated from the model of a homogeneously charged sphere where the Coulomb radius  $R_C$  is taken from the root-mean-square (rms) radius of the double-folding potential.

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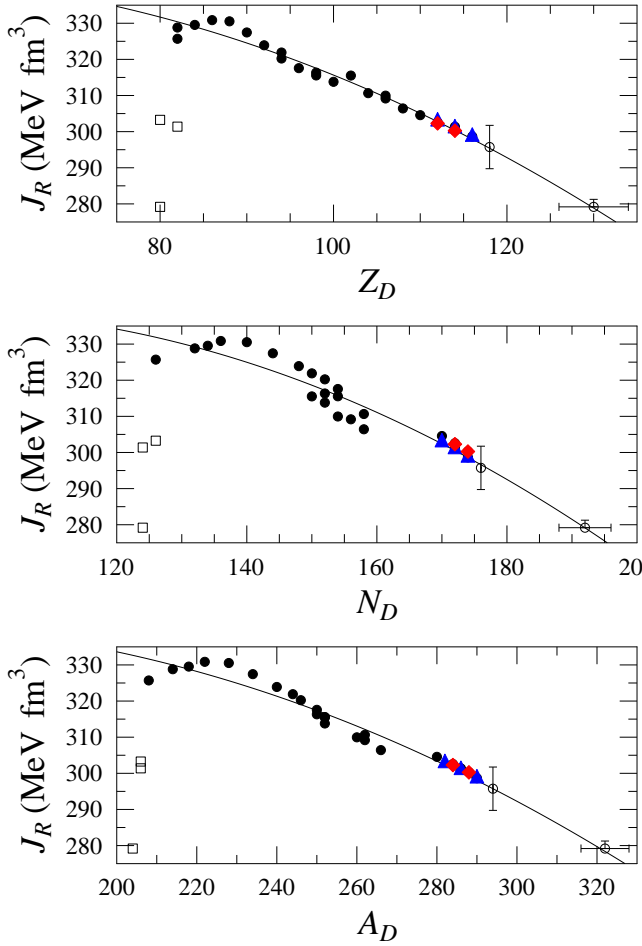


FIG. 1. (Color online) Volume integrals  $J_R$  for superheavy nuclei as a function of  $Z_D$  (upper),  $N_D$  (middle), and  $A_D$  (lower). Data for chain-1 (blue triangles) and chain-2 (red diamonds) have been added. Otherwise, this figure is identical to Fig. 3 of my previous study [2]; the lines are quadratic fits to the experimental data available in 2006.

The strength parameter  $\lambda$  is adjusted to reproduce the experimental  $Q_\alpha$ ; i.e., the potential  $V(r)$  has an eigenstate at the correct energy with a chosen number of nodes in the corresponding wave function ( $N = 11$  in the present case of  $0^+$  ground states of even-even superheavy nuclei; see [2]). The resulting  $\lambda$  values and volume integrals  $J_R$  of the nuclear potential are given in Table I for chain-1 and chain-2. In addition, Fig. 1 shows  $J_R$  as a function of the proton number  $Z_D$ , neutron number  $N_D$ , and mass number  $A_D$  of the daughter nucleus. Fig. 1 is a copy of Fig. 3 of my previous study [2] where recent experimental data for chain-1 and chain-2 have been added. It is obvious from Fig. 1 that the volume integrals  $J_R$  show a regular and smooth dependence of  $Z_D$ ,  $N_D$ , and  $A_D$ , which can be used to obtain reliable estimates for unknown nuclei. Discontinuities of  $J_R$  appear only at shell closures, e.g. at the doubly-magic daughter nucleus  $^{208}\text{Pb}$  (see Fig. 1 and [2]).

In a next step the  $\alpha$ -decay half-lives  $T_{1/2,\alpha}^{\text{calc}}$  are calcu-

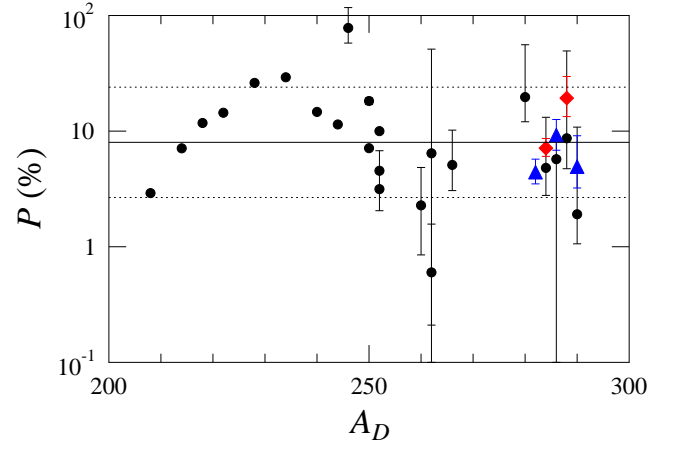


FIG. 2. (Color online) Preformation factors  $P$  as a function of the mass number  $A_D$  of the daughter nucleus, taken from [2] and extended by data for chain-1 (blue triangles) and chain-2 (red diamonds). The horizontal lines indicate an average value of  $P \approx 8\%$  (full line) and typical uncertainties of a factor of three (dotted lines); taken from [2].

lated from the transmission through the barrier of the potential in Eq. (1) using the semi-classical formalism of [31]. And finally the preformation factor  $P$  is calculated from the ratio

$$P = \frac{T_{1/2,\alpha}^{\text{calc}}}{T_{1/2,\alpha}^{\text{exp}}} \quad (2)$$

The resulting preformation factors are shown in Fig. 2 which is a repetition of Fig. 1 of [2] with the additional results for chain-1 and chain-2. An average value of about 8% for  $P$  was found in [2], and the new data for chain-1 and chain-2 fit nicely into this systematics. Because  $\alpha$ -decay is the dominating decay mode of the nuclei in chain-1 and chain-2 (except  $^{286}\text{Fl}$  [32]), in the following the subscript  $\alpha$  is omitted in  $T_{1/2}$ .

The very smooth and systematic behavior of the volume integrals  $J_R$  in Fig. 1 can be used for the prediction of unknown  $Q_\alpha$  values. Instead of adjusting the strength parameter  $\lambda$  to experimentally known  $Q_\alpha$ , the strength parameter  $\lambda$  is now fixed from neighboring nuclei, and from the resulting potential  $V(r)$  the eigenstate energy is calculated. This is illustrated in Fig. 3:  $\lambda = 1.1458 \pm 0.0010$  is estimated for  $^{296}\text{118}$ . This estimate for  $\lambda$  is well constrained by the similar slope of  $\lambda(Z)$  for chain-1 and chain-2 and by the small and almost constant difference between chain-1 and chain-2.

The potential  $V(r)$  with the strength parameter  $\lambda = 1.1458$  has the eigenstate with  $N = 11$  nodes at  $Q_\alpha = 11.655 \text{ MeV}$ . The small uncertainty of  $\lambda$  translates to an uncertainty of  $Q_\alpha$  of only 95 keV. Thus, the present study predicts  $Q_\alpha = 11.655 \pm 0.095 \text{ MeV}$  for the unknown nucleus  $^{296}\text{118}$ . This result is very close to the predictions of the selected mass models WS3+ and WS4+ and slightly lower than the mass model HN [1]. It is interesting to

TABLE I. Parameters of the  $\alpha$ -decays in chain-1 and chain-2. Experimental values are taken from [32].

	decay	$Q_\alpha$ (MeV)	$\lambda$	$J_R$ (MeV fm <sup>3</sup> )	$T_{1/2}^{\text{calc}}$ (s)	$T_{1/2}^{\text{exp}}$ (s)	$P$
chain-1	$^{286}\text{Fl} \rightarrow ^{282}\text{Cn}$	10.35	1.1633	302.86	$8.48 \times 10^{-3}$	$2.0 \times 10^{-1}$	0.0424
chain-1	$^{290}\text{Lv} \rightarrow ^{286}\text{Fl}$	11.00	1.1568	300.96	$7.36 \times 10^{-4}$	$8.3 \times 10^{-3}$	0.0887
chain-1	$^{294}118 \rightarrow ^{290}\text{Lv}$	11.82	1.1486	298.63	$3.27 \times 10^{-5}$	$6.9 \times 10^{-4}$	0.0473
chain-2	$^{288}\text{Fl} \rightarrow ^{284}\text{Cn}$	10.07	1.1615	302.29	$4.70 \times 10^{-2}$	$6.6 \times 10^{-1}$	0.0713
chain-2	$^{292}\text{Lv} \rightarrow ^{288}\text{Fl}$	10.78	1.1545	300.26	$2.51 \times 10^{-3}$	$1.3 \times 10^{-2}$	0.1930
chain-2	$^{296}118 \rightarrow ^{292}\text{Lv}$	$11.655 \pm 0.095^{\text{a}}$	$1.1458^{\text{b}}$	297.80	$7.30 \times 10^{-5}$	$8.25 \times 10^{-4\text{c}}$	$0.0885^{\text{d}}$

<sup>a</sup> calculated using  $\lambda = 1.1458 \pm 0.0010$

<sup>b</sup> extrapolated from neighboring nuclei; see Fig. 3

<sup>c</sup>  $T_{1/2}^{\text{predict}}$

<sup>d</sup> average of neighboring nuclei; see Fig. 4

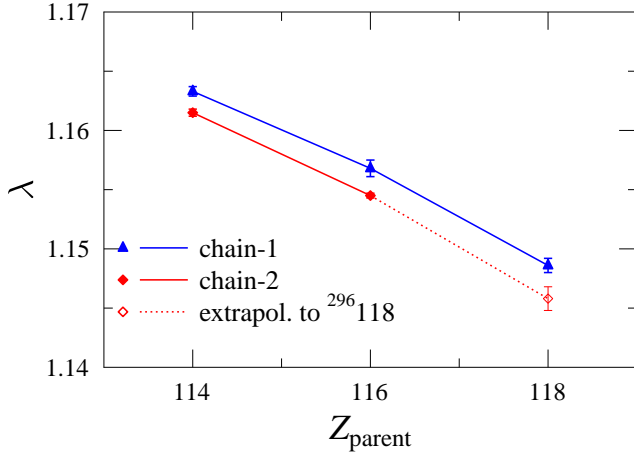


FIG. 3. (Color online) Potential strength parameter  $\lambda$  for chain-1 (blue triangles) and for chain-2 (red diamonds). The full symbols are derived from experimental data [32]; the open diamond is the extrapolation for the unknown nucleus  $^{296}118$ . Further discussion see text.

note that already the fits of  $J_R$  in Fig. 1 (taken from [2] and based on the available data in 2006) predict  $\lambda$  between 1.1413 and 1.1463 for  $^{296}118$ , corresponding to  $Q_\alpha$  between 11.6 MeV and 12.1 MeV which is almost exactly the range of  $Q_\alpha$  from the three selected mass models WS3+, WS4+, and HN in [1].

Finally, the half-life of  $^{296}118$  can be calculated from this potential with  $\lambda = 1.1458$ . The result is  $T_{1/2}^{\text{calc}} = 73.0 \mu\text{s}$ . According to Eq. (2), for a prediction of the experimental half-life  $T_{1/2}^{\text{exp}}$ , the calculated half-life has to be divided by the preformation factor  $P$ . Taking the average preformation factor  $P_{\text{av}} = 0.0885$  of chain-1 and chain-2, one finally obtains  $T_{1/2}^{\text{predict}} = 0.825 \text{ ms}$ .

A careful estimate of the uncertainty of the preformation factor  $P$  can be read from Fig. 4. The average value of the 5 known  $P$  in chain-1 and chain-2 is  $P_{\text{av}} = 0.0885$ . However, all  $P$  have significant uncertainties which result from the uncertainties of the experimental  $\alpha$ -decay half-lives, and the  $P$  vary between 0.0424 for  $^{286}\text{Fl}$  in chain-1 and 0.193 for  $^{292}\text{Lv}$  in chain-2. Thus, I estimate the uncertainty of  $P$  for  $^{296}118$  from the highest

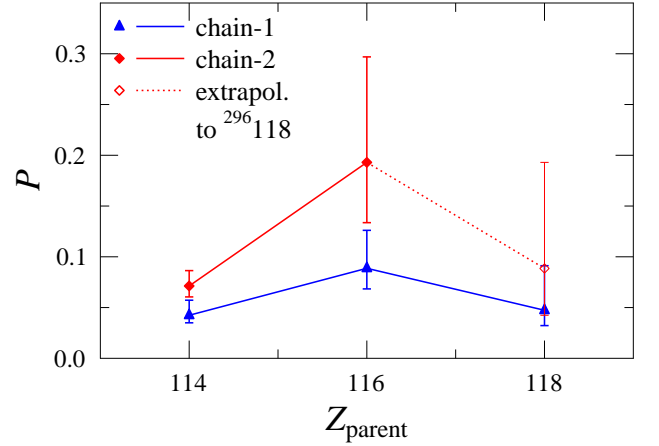


FIG. 4. (Color online) Extrapolation of the preformation factor  $P$  to  $^{296}118$ .

and smallest values of  $P$  in chain-1 and chain-2, leading to  $P = 0.0885^{+0.1045}_{-0.0461}$ . Again it is interesting to note that my earlier study in 2006 [2] found very similar values of  $P \approx 0.08$  with an uncertainty of a factor of three.

The uncertainty of the predicted half-life  $T_{1/2}^{\text{predict}} = 0.825 \text{ ms}$  can be estimated from the uncertainties of  $Q_\alpha$  and  $P$ . The uncertainty of  $Q_\alpha$  of about 100 keV translates to a factor of about 1.7 for the uncertainty of the half-life, and the uncertainty of  $P$  of slightly above a factor of two enters directly into the uncertainty of  $T_{1/2}^{\text{predict}}$ . Combining both uncertainties results in a factor of about 4 uncertainty for the predicted half-life; i.e., the half-life of  $^{296}118$  should lie in between 0.2 ms and 3.3 ms.

In summary, I have used the smooth and regular behavior of the strength parameter  $\lambda$  of the  $\alpha$ -nucleus double-folding potential to estimate the  $\alpha$ -decay energy  $Q_\alpha$  of the unknown nucleus  $^{296}118$ . The prediction of  $Q_\alpha = 11.655 \pm 0.095 \text{ MeV}$  is completely independent of mass formulae, but nevertheless in excellent agreement with the results from the selected mass formulae in [1]. From the barrier transmission and from the preformation  $P$  of about 9%, a half-life for  $^{296}118$  of 0.825 ms is predicted with an uncertainty of a factor of 4. These predictions for the  $Q_\alpha$  value and for the  $\alpha$ -decay half-life of

$^{296}\text{118}$  may help to guide experimentalists, and hopefully, these predictions can be confronted with experimental results in the near future.

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